Crystal-based Approach to Beam Collimation in RHIC and SNS

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Abstract

Bent crystal serving as a scraper of the beam collimation system can channel halo particles directly into the absorber. By means of computer simulations, we analyse the capabilities of crystal technique for the beam cleaning process. Two applications are considered: the crystal collimator now being installed into RHIC for cleaning of the fully stripped gold ions, and a similar system being developed for the Accumulator Ring of the Spallation Neutron Source.

1 Introduction

Classic two-stage collimation systems for loss localisation in accelerators typically use a small scattering target as a primary element, whereas the secondary element is a bulk absorber [1]. Normally in colliders and storage rings the halo diffusion is pretty slow, therefore the first touch of a halo particle with the aperture-restricting collimator is rather a glancing touch, with the impact parameter on the order of micron. Such a near-surface particle is easiely scattered out of the collimator material. The role of the primary element is to give a substantial angular kick to incoming halo particles in order to increase the impact parameter of the particles on the secondary element placed in some position, optimised transversally and longitudinally for better interception.

Naturally, an amorphous target scatters particles in all possible directions. Ideally, one would prefer a *"smart target"* that kicks all particles in only one direction: for instance, only in radial plane, only outward, and only into the preferred angular range corresponding to the center of absorber (to exclude escapes). Bent crystal is the first idea for such a smart target: it traps particles as much as possible and convenes them into desired direction. In physics language, we replace the scattering on single atoms of amorphous target by the coherent scattering on atomic planes of aligned monocrystal.

If the crystal channeling efficiency would be 100%, the crystal would serve as a kicker putting all the beam particles deeply onto the collimator for safe absorption. A real crystal is not 100% efficient, therefore only part of the beam goes into safe place, whereas the rest of the particles are scattered and then handled in traditional way by collimators.

Several issues may be important for real application of this technique for beam cleaning: channeling efficiency, withstanding a high beam intensity, long lifetime of crystal. Recently the crystal team of IHEP has demonstrated the following milestones.

- The channeling crystal withstand the intensity of 2×10^{14} 70-GeV proton hits per spill of $\sim$0.5 s duration [2]. This corresponds to averaged (over days) intensity of 2×10^{13} proton/s at crystal, already higher than the expected 0.1% beam loss in the SNS Accumulator Ring ($=1.2\times10^{13}$ p/s).
  In a special pulse-mode test, one of the crystals was exposed to even more extreme dump, $\sim10^{14}$ proton hits in short 50-ms pulse with repetition rate once per 9.6 s. The later external-beam test has shown that this crystal retained normal channeling properties [2].

- Several crystals have been in exploitation at high intensity (order of $5\cdot10^{11}$ extracted protons in every spill) for 1-2 months [2]. As a result, the integrated dose of proton hits at the crystal has been about 10^{20}/cm^2 After this irradiation to 10^{20}/cm^2 the crystal extraction efficiency remained the same as measured in the beginning of physics run and at the end. Though high it is, the achieved integral irradiation is still below the world highest results obtained in BNL [3] and CERN [4], (4–5)$\times10^{20}$ proton/cm^2. The CERN experience showed that at the achieved threshold of 5×10^{20} p/cm^2 at 450 GeV the crystal lost 30% of its deflection efficiency. At 450 GeV, crystal is sensitive to lattice misalignment of $\sim$5 μrad, while at the SNS energy it is tolerant to $\sim$100 μrad, therefore crystal may withstand higher doses at SNS, $\sim10^{21}$ p/cm^2. One of the IHEP crystals did extract 70-GeV protons over 10 years without replacement!

- The experimentally demonstrated figures of crystal deflection efficiency are 65% (IHEP, 70 GeV slow extraction [2]) and 60% (CERN, 450 GeV external beam deflection[4]), here efficiency is the ratio of the deflected beam to all incident beam. It's been earlier demonstrated in IHEP experiment that crystal scraper (channeling then with 50% efficiency) has reduced two-fold the radiation levels downstream in the machine [5].

This year, in the framework of the project to design and test a collimation system prototype using bent channeling crystal for cleaning of the RHIC heavy ion beam halo, a silicon (110) single crystal is being installed into the vacuum chamber of one of the RHIC rings with proposition of being a primary element situated upstream of the traditional heavy "amorphous" collimator [6].

The activities on crystal collimation concept have been largely supported by simulations of the impact that the improvement in scraping efficiency would have on the radiation backgrounds in the machines. Making use of computer code CATCH [9] for crystal simulations, earlier extensively verified in CERN, Fermilab, and IHEP experiments in 1992-2000 [10], it's been shown in Tevatron scraping simulations that crystal scraper reduces accelerator-related background in CDF and D0 experiments by a factor of 10 [11].

For the application in the SNS one can take a 100%-safe approach: using a 1-mm bent Si crystal together (just in front) with normal primary scraper (like 5 mm Pt or W) of the collimation system, in the same location. First, this ensures that if crystal is not channeling then the system works as usual. When crystal is brought to channeling condition, it works just as a *"crystalline edge"* for the primary target, deflecting ("shaving off") at ∼5 mrad as much halo as possible. In this way, the deflected particles will also be scattered then in the Pt target, therefore the actual resulting deflection will be rather in some range; this may even have an additional positive effect, spreading the beam load on the absorber over some larger area. The crystal scraper protects the edge of absorber from heat and radiation load.

The above said is a strong motivation to pursue the experimental tests of crystal-assisted collimation of beams in order to evaluate the potential benefits for the beam collimation systems. The experimental studies on beam collimation in 1 GeV range are under progress in the main ring of the IHEP U-70 accelerator, performed jointly by the collaboration of BNL/SNS and IHEP during 2000 [12]. The following stage of the experimental program will make use of crystalline scrapers dedicated to 1 GeV studies.

2 Crystal Scraper

As the crystal can be aligned to the beam envelope, then to first approximation all the incoming halo particles are parallel to the crystal planes thus ensuring a high efficiency of channeling. How parallel they are, depends on a beam growth rate.

In case of RHIC gold ion beam, the intrabeam scattering provokes a pretty rapid growth of the beam. On the other hand, the location chosen for the bent crystal has a huge beta function, in excess of 1000 m. The earlier performed modelling of beam diffusion in RHIC [6] has provided us with a sample of halo particles that have a divergence at the incidence on the crystal of a few microradian, well within the critical angle of channeling in silicon, $\theta_c = \pm 10$ μrad at the RHIC energy of 250 GeV per unit charge.

The crystal situated ∼8 m upstream of a massive collimator is bending the incoming particles by 0.5 mrad. As computer simulations show, the efficiency of bending at 0.5 mrad for the considered sample of particles is over 70%. If we include all the particles bent at least 0.1 mrad (they are still well intercepted by collimator), the bent fraction amounts to 78%.

For the SNS, the beam loss scenario is pretty unknown yet. Therefore, we study the effect of crystal scraper [7] as a function of divergence of the particles intercepted by a crystal. Figure 1 shows the bending effect when the incident particles are well within the angular acceptance of the silicon (110) crystal planes, $2\theta_c$=0.25 mrad at the SNS kinetic energy of 1.3 GeV.

The particles that were not channeled in the crystal get some scattering, nearly the same as in an amorphous matter. Later, these unchanneled particles might be intercepted by crystal again and channeled on this later encounter. Multiple encounters of particles with channeling crystal essentially improve the chances to enter the channeling mode in crystal [8]. In the experiments on "multipass" crystal extraction this

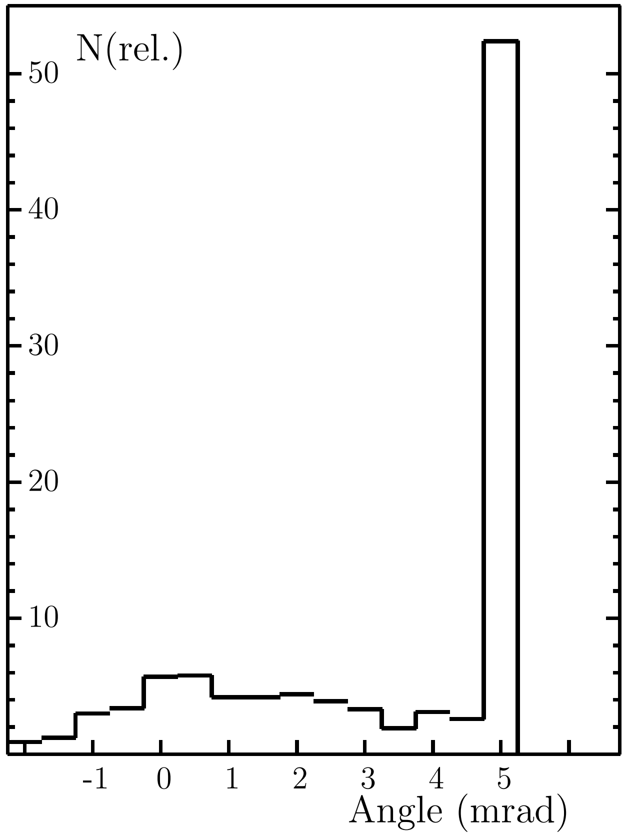

Figure 1: Angular distribution of 1.3 GeV protons downstream of a 0.5-mm single silicon crystal scraper with 5-mrad bending, for a parallel incident beam.

happens automatically, as the particles scattered in crystal go on circulating in the ring and occasionally may encounter crystal again.

In some cases it's not that easy to have multiple encounters with a single crystal. For instance, the SNS has a rapid-cycling Accumulator Ring, 60 Hz, with a beam lifetime about 1200 turns, and it's not obvious that particles once scattered in a crystal will encounter it again. Moreover, the behaviour of near-aperture particle can be quite complicated, and the beam instability driving the halo can be quite fast. In the case of RHIC, as a result of huge beta in the cleaning insertion, the scattering in crystal increases the betatron amplitude by sort of millimeters; this again makes it unobvious that the scattered particles, after some circulation in the ring, will likely come to crystal again.

The alternative to "automatic" multiple encounters with a single crystal scraper is to install several (two, three, or more) crystals in a row. Then each of them must be aligned (or pre-aligned) in position and angle. This would complicate the mechanics and procedures, but at the moment we are interested only in potential physics benefits.

As the scattering of unchanneled particles in crystal increases their divergence and hence affects the chances of channeling on a later encounter with a crystal, one should further optimise the length of a crystal to improve in overall probability of channeling as a result of several encounters with a crystal.

For the same sample of gold particles in RHIC, we modelled their successive encounters with a crystal. For RHIC, the optimum crystal for 0.5 mrad bending is about the size already chosen for the real prototype of crystal collimator now ready for the beam tests. Figure 2 shows how the efficiency of crystal bending increases with the number of particle encounters with a crystal (4 mm long Si(110)).The first encounter provides the bending efficiency of just under 80%. The bent fraction (we count here all particles deflected more than 0.1 mrad toward the collimator) becomes order of 90% after about 3rd encounter, 95% after 7th, and over 97% after about 10 encounters with 4-mm crystal.

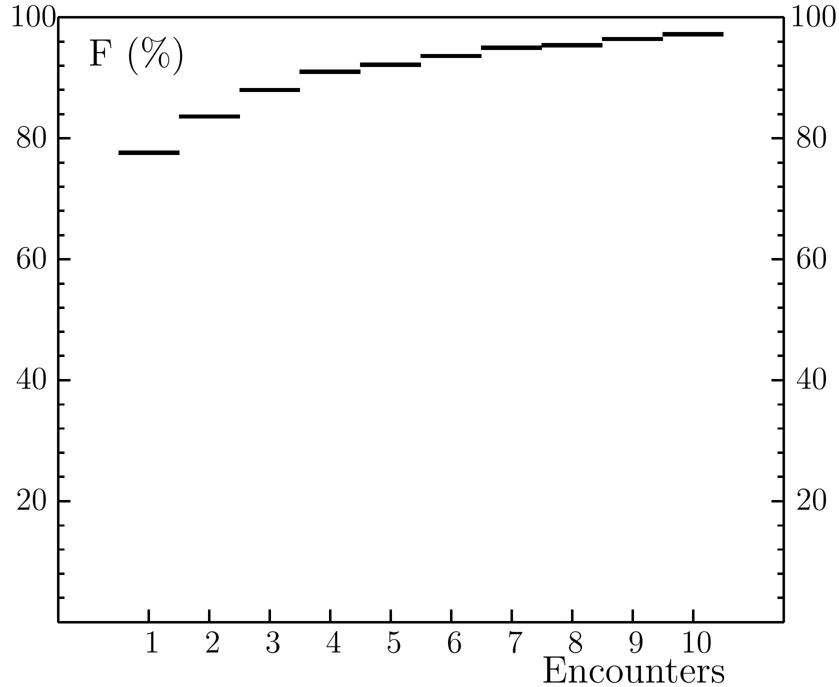

Figure 2: The fraction of bent Au ions as a function of the number of encounters with a crystal.

Although this figure may look impressive, 30-fold reduction of backgrounds by crystal alone, it's not simple to realise technically. Either one installs 3–10 crystals in a row in same location, with a few-μm precision in relative radial position x and a few-μrad precision in the angle x'; which is possible but may be a substantial headache. Or one installs a single crystal but takes care that particles scattered of the crystal are not intercepted elsewhere and likely will hit the crystal again on later turns.

Actually with every scattering in a 4-5 mm crystal the particles gain $\sim$1 mm in betatron amplitude in this location. This means that our crystal may have 2–3 encounters per particle, after that the scattered particle is likely to be lost elsewhere. Still, 2–3 encounters make a good improvement as shows Figure 2.

For the SNS the optimum for the crystal size should obviously be quite smaller if we take into account increased scattering angles near 1 GeV. Although a single crystal of $\sim$1 mm size (already in use in IHEP) provides a similar efficiency for a parallel beam as in RHIC case, a multi-crystal approach requires much shorter crystals. Luckily, there is a technique of graded composition $Si_{1-x}Ge_x$/Si strained layers which form a bent crystal lattice of uniform curvature [13] with any thickness along the beam direction from only 1 μm up to millimeters, having a big cross-section (many centimeters) at the same time. This technique limits the acievable bending angle at the SNS energy to order of 2 mrad

[13]. We optimised the crystal size in that case and found the optimum crystal to be about 70 μm along the beam, for the case of 2 mrad bending.

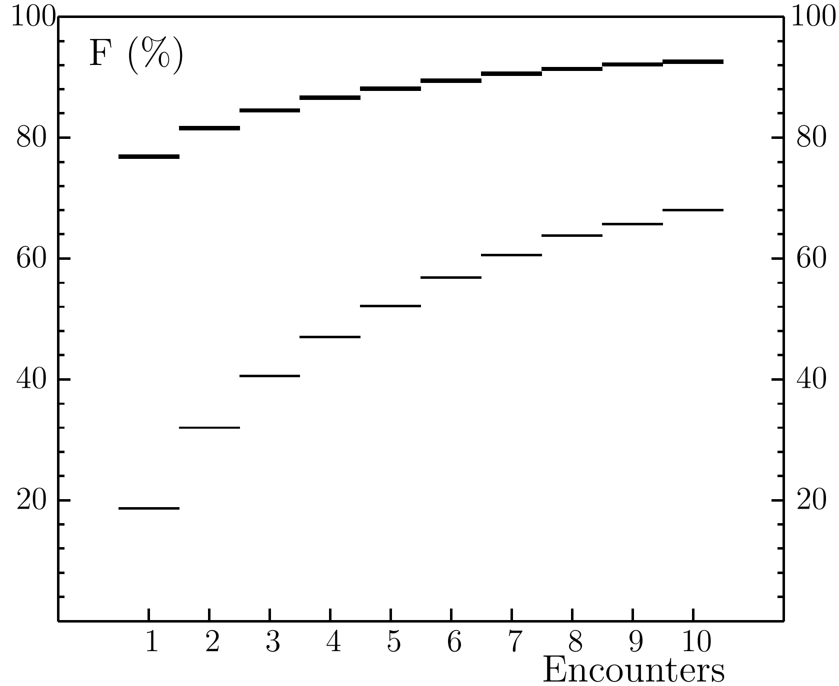

Figure 3: The fraction of 1.3 GeV protons bent more than 1 mrad, as seen downstream of a $10\times70\mu$ multi-crystal silicon scraper, as a function of the encountered number of crystals. For a parallel incident beam (top, thick line), and for the beam incident with ±0.5-mrad divergence (bottom, thin line).

Figure 3 shows how the bent fraction of 1.3 GeV protons increases with the number of Si crystals encountered. In this example we have first taken a parallel incident beam, and showed in the Figure all the particles bent more than 1 mrad. After the first encounter, 73% of particles are found at 2 mrad, in the channeled peak, and 77% of particles are in the region of $\geq$1 mrad. The bent fraction comes over 90% on about 6th encounter, and totals near 93% after 10 encounters with 70 μm crystal.

This simulation was repeated with a divergent incident beam (1 mrad full width, flat distribution), with the results shown in Figure 3 (thin line, bottom). Very interesting feature is that – whereas the efficiency of a single encounter drops expectedly – the multiple encounters boost the bending effect essentially. The diverging particles, unchanneled first, modify their angles with scattering and eventually fit the crystallographic direction. After 10 crystals, 56% of the beam is found in the channeled peak at 2 mrad.

We studied further the effect of multi-crystal at several divergences. As shows Figure 4, while a single crystal scraper drops the efficiency when the divergence of incident particles goes in a range of milliradians, the pack of ten 70-μm crystals is efficient through this range.

Essential technological difference of the SNS case from the RHIC one is that all 10 wafers of $Si_{1-x}Ge_x$/Si can be packed together in a single unit (about $10\times70\mu$ =0.7 mm along the beam and some centimeters across) before installing it into the accelerator.

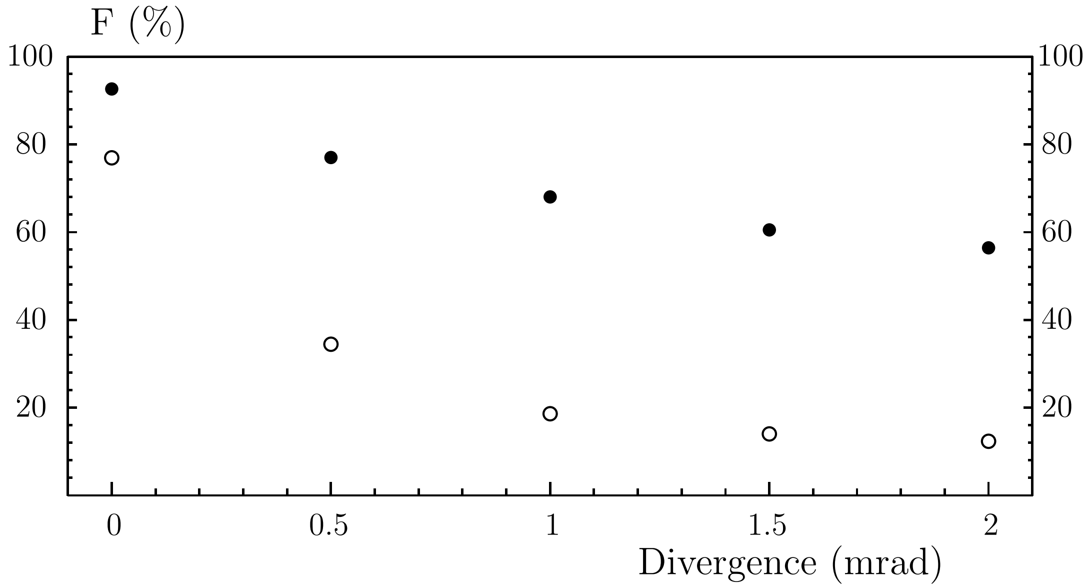

Figure 4: The fraction of bent 1.3 GeV protons as a function of divergence of the incident beam. After one crystal (o) and after 10 crystal encounters (•).

The 10 wafers can be *pre*-aligned to each other when they are mounted together into a single unit. This is easy in the SNS case because the needed accuracy of alignment is low; as shows Figure 4, if wafers are misaligned to the beam by sort of milliradian, they still channel a substantial part of the beam. This also means that the unit, 10-pack of crystals, will have to be aligned to the beam envelope with same accuracy; an accuracy of a fraction of milliradian might do the job. Potentially, such a low demand for accuracy might even mean that after installation of the crystal target into vicinity of the beam one doesn't need anymore adjustment of its angle.

3 Conclusion

Our computer simulations of crystal channeling show that 80-95% of the incident halo particles in the rings of RHIC and SNS can be channeled directly into the absorber. The collimation system then has to intercept the remaining few particles only. This may give the factor of 5-20 improvement in the collimation efficiency.

An approach with multi-crystal scraper can be useful also in the cases where the same scraper must handle beams in a broad range of energies (e.g., during acceleration). Then the first crystal can be thin, dedicated to low-end of the energy range, while the next crystal is optimised for high-end of the range.

Further bending techniques and crystal materials can be investigated, including for instance low-Z (diamond) and high-Z (germanium, tungsten) [4, 14], as options for scraping facilities.

References

[1] J.B.Jeanneret, Phys. Rev. ST Accel. and Beams 1, 081001 (1998)

[2] Yu.A.Chesnokov et al., *Using Bent Crystals for Loss Localization in IHEP Accelerator*, EPAC'2000. V. I. Kotov *et al.*, EPAC 2000 Proceedings (Vienna), p.364. CERN-LHC-2000-007-MMS (Dec 2000) 4p. [arXiv:hep-ex/0111001].

[3] S.I.Baker et al., Nucl. Instr. Meth. B 90 (1994) 119.

[4] A.Baurichter et al., Nucl. Instr. Meth. B 164-165 (2000) 27.

[5] A.G.Afonin, V.M.Biryukov, V.N.Chepegin et al., "New projects of crystal extraction at IHEP 70-GeV accelerator". Particle Accelerator Conference Proceedings (New York, 1999); CERN LHC 99-2 (MMS), Geneva 1999. [arXiv:hep-ex/0111028].

[6] D. Trbojevic *et al.*, "A study of RHIC crystal collimation," EPAC Proceedings (Stockholm, 1998), p.2146 [arXiv:hep-ex/0111021].

[7] V. M. Biryukov. PAC 1999 Proceedings (New York), pp.1240-1242. [arXiv:hep-ex/0111034].

[8] V.M. Biryukov, *Nucl. Instr. and Meth. B* **53** 202 (1991). A.M. Taratin et al. *Nucl. Instr. and Meth. B* **58** 103 (1991)

[9] V.M. Biryukov, "Crystal channelling simulation: CATCH 1.4 user's guide," CERN-SL/Note 93-74 (1993) [arXiv:hep-ex/0110046]. V.M. Biryukov, *Phys. Rev. E* **51** (1995), 3522; **52** (1995), 2045; **52** (1995), 6818; *Phys. Rev. Lett.*, **74**, 2471 (1995)

[10] H. Akbari et al., *Phys. Lett.* **B 313** (1993), 491 V. M. Biryukov, V. I. Kotov and Y. A. Chesnokov, Phys. Usp. **37**, 937 (1994). A.G. Afonin et al., Phys. Lett. **B 435** (1998), 240. R. A. Carrigan *et al.*, Nucl. Instrum. Meth. B **90**, 128 (1994). C.T. Murphy et al., *Nucl. Instr. and Meth. B* **119** (1996), 231 R. A. Carrigan *et al.*, Phys. Rev. ST Accel. Beams **1**, 022801 (1998).

[11] V.M.Biryukov, A.I.Drozhdin, N.V.Mokhov. 1999 Particle Accelerator Conference (New York). Fermilab-Conf-99/072 (1999).

[12] N.Catalan-Lasheras et al., EPAC Proceedings (Vienna 2000)

[13] M.B.H.Breese, *Nucl. Instr. Meth.* **B 132**, 540 (1997)

[14] V. M. Biryukov, Nucl. Instrum. Meth. B **117**, 463 (1996) [arXiv:hep-ex/0110018],

[15] More papers on the subject of crystal bending can be found at http://beam.ihep.su/crystal.html